METHODS AND APPARATUS FOR POLARIZATION CONTROL

BACKGROUND OF THE INVENTION

[0001] The present invention is generally applicable to communications systems. More particularly, the present invention is applicable to polarization control in optical communications systems that suffer from dead spot problems.

[0002] Communications systems employing optical equipment have long been used to provide high bandwidth transmission of vast amounts of data. Enhanced signaling techniques have been implemented in order to achieve even greater throughput, particularly for long distance ("long haul") transmission. One important technique employs polarization. For an optical signal, polarization, or the state of polarization (SOP), represents the amplitude and direction of the electric field vector of the light signal.

[0003] By way of example only, an aggregate or composite optical signal may transmit numerous channels, each having a different wavelength and a different polarization. The channels can be polarized so that, e.g., all even channels are polarized to a first polarization state and all odd channels are polarized to a second polarization state. The first and second polarization states may be orthogonal to one another, substantially reducing unwanted cross talk between adjacent channels. Orthogonal polarization, also known as "orthogonal launch," is more fully explained in U.S. Patent No. 6,134,033, entitled "Method and Apparatus for Improving Spectral Efficiency in Wavelength Division Multiplexed Transmission Systems" and U.S. Patent No. 6,459,515, entitled "Method and Apparatus for Transmitting a WDM Optical Signal Having States of Polarization That Are Pairwise Orthogonal," the entire disclosures of which are fully incorporated by reference herein.

[0004] A critical issue when employing polarized signals is maintaining the SOP along the transmission path. For

example, as signals are transmitted over optical fiber, the SOP may fluctuate based on a variety of factors, such as the type of fiber, the length of the fiber, manual handling, etc. Single-mode fibers, e.g., fibers that propagate only one mode above a cutoff wavelength, may not preserve the SOP of signals propagating through the optical fiber. In order to address SOP fluctuations, polarization-maintaining equipment is necessary. However, employing polarization-maintaining equipment throughout the transmission system may be extremely expensive or impractical. Thus, polarization controllers may be employed instead to alter the polarization state of the optical signal.

[0005] Polarization controllers receive an input SOP at a point along the transmission path and output an optical signal that will have a desired SOP at some later point along the transmission path. Typically, a polarization controller is composed of one or more "waveplates.". As used herein, optical elements that exhibit birefringence are collectively referred to as waveplates. Birefringence is the separation of an incident light beam into a pair of diverging beams, known as "ordinary" and "extraordinary" beams. The velocities of the ordinary and extraordinary beams through the birefringent material vary inversely with their refractive indices. The difference in velocities gives rise to a phase difference when the two beams recombine. Waveplates can generate full, half and quarter-wave retardations when the phase difference equals whole, half and quarter wavelengths. Waveplates can also generate any arbitrary fractional-wave retardations. Various devices may be employed in a polarization controller, and modeled as a waveplate or combination of waveplates. Controller implementations can be classified into two types based on how the waveplate(s) operates: (1) devices based on control of waveplate birefringence while the effective waveplate axis is fixed, and (2) devices based on controlling the orientation

of the waveplate about its axis while the birefringence is unchanged. Liquid crystal and fiber squeezer devices may fall into the first category while $LiNbO_3$ waveguide devices and fiber loop devices may fall into the second category.

[0006] FIG. 1(a) illustrates an exemplary set of three (3) waveplates 10, 12 and 14 that can have their orientations (angles of rotation α, β, γ) changed while the birefringence is unchanged. As seen in the figure, an input SOP 16 can be modified by changing the orientation of the waveplate 10 to achieve a first intermediate SOP 18. The first intermediate SOP 18 can be modified by changing the orientation of the second waveplate 12 to achieve a second intermediate SOP 20. The second intermediate SOP 20 can be modified by changing the orientation of the third waveplate 14 to achieve an output SOP 22.

[0007] FIG. 2(a) illustrates an orthogonal launch transmission system implementing polarization controllers. Inputs 100a,b transmit signals to polarization controllers 102a,b along fibers 104a,b, which may be single mode fibers. The pair of polarization controllers 102a,b operate on the input signals and pass optical signals 114a,b along a second pair of fibers 106a,b. The signals 114a,b are then multiplexed together by a multiplexer ("MUX") 108 to form a multiplexed signal 116. The multiplexed signal 116 is transmitted through an undersea optical cable (or "wet plant") 110. A second portion of the multiplexed signal 116 is split by a polarization splitter 112, and used to provide feedback to the pair of polarization controllers 102a,b.

[0008] FIG. 2(b) illustrates a conventional single-channel polarization tracking receiver/filter implementing a polarization controller 200, which receives the multiplexed signal 116 from the wet plant 110. The polarization controller 200 operates on the multiplexed signal 116 and outputs a signal 206 to a polarization splitter 202. The polarization splitter 202 can separate a single channel

(e.g., signal 208a) from the signal 206. The signal 208a is then provided to a receiver 204. A signal 208b is passed through an optical filter 210 and transmitted to the polarization controller 200 as a feedback signal. While only one polarization controller is shown in FIG. 2(b), it should be understood that separate polarization controllers 200 are employed for each channel.

[0009] One major concern in such transmission systems is the situation where the input SOP of an optical signal results in a feedback signal that is insensitive to the dithering or phase shifting of the rotational angle of the waveplate. This is known as "loss control." The inventors of the instant application have identified loss control problems in both simulations and experiments. Others have also acknowledged loss control in the past, and have claimed the problem to be unavoidable. See, for example, Shieh et al., "Dynamic Eigenstates of Polarization," IEEE Photonics Technology Letters, Vol. 13, No. 1, pp. 40-42, January 2001, which is fully incorporated by reference herein. If loss control is not addressed in the polarization controller (either on the transmit side or on the receive side), it may not be possible to achieve a desired output SOP. The states that create loss control problems are known as "dead spots." It is difficult to move away from a dead spot once it has been reached because conventional polarization controllers are not capable of making appropriate adjustments to the waveplates or other devices that they use. When a dead spot happens for a specific combination of waveplates in the polarization controller and a specific input SOP, small variations in the input SOP will require large changes to one or more of the waveplates to transform the input SOP to the desired output SOP. With a conventional dithering algorithm, however, the waveplates cannot be rotated by a large angle. Thus, in that situation, the output SOP may move away from a desired output SOP when the input SOP varies, resulting in a

loss control situation. Dead spots can seriously degrade system performance and result in loss of received data due to co-channel interference and other problems.

[0010] Some conventional polarization controllers employ polarimeters. A polarization controller based on a polarimeter needs to know the birefringence transfer function from an input polarization state to the desired output polarization state through the controller device and transmission line (e.g., a single mode fiber). Determining the exact birefringence transfer function is not feasible in actual commercial systems. Thus, achieving a desired output polarization state is problematic. Other conventional polarization controllers have used a simple dithering algorithm based on the feedback signal from a polarization splitter to adjust the SOP. The dither algorithm is insensitive to, e.g., aging-induced drifting of controller device parameters such as DC bias voltage. For examples of polarization controllers employing the conventional dither algorithm, see "Analysis of a Reset-Free Polarization Controller for Fast Automatic Polarization Stabilization in Fiber-optic Transmission Systems," Journal of Lightwave Technology, Vol. 12, No. 4, April 1994, and U.S. Patent No. 5,212,743, both to Fred L. Heismann, which are fully incorporated by reference herein. In the Heismann references, a reset-free polarization controller is employed, which consists of several quarter-waveplates (QWP) and half-waveplates (HWP).

[0011] Specifically, a HWP is sandwiched between a pair of QWPs. The conventional approach is to dither the rotational angle of each waveplate as graphically illustrated in FIG. 3. The angle of the waveplate is dithered/adjusted by a small step-size ($\Delta\alpha$, $\Delta\beta$, or $\Delta\gamma$) in sequence. More specifically, the angle α of the first waveplate is dithered/adjusted (e.g., by mechanically rotating the waveplate) for a fixed time period, then the angle β of the second waveplate is

dithered/adjusted for a fixed time period, and finally the angle γ of the third waveplate is dithered/adjusted for a fixed time period. Thus, each waveplate is independently dithered and adjusted for a fixed amount of time. Unfortunately, this approach may not have a sufficient control speed to handle fluctuations in the input SOP. This can result in a loss control problem.

[0012] There exist two situations that explain loss control and consequent reduction of the control speed. As used herein, control speed means that a polarization controller can track any random movement of the input SOP with a specific speed such that the desired output SOP is locked at some later point along the transmission path. In the first situation, there is little or no absolute response by dithering a waveplate (controlling the waveplate angle). In other words, the SOP may not change regardless of how much a particular waveplate is dithered. As an example, a HWP controller only transforms right (or left) circular polarization state at the input to left (or right) circular polarization state at the output independent of the rotation angle of the waveplate, which is the control parameter.

[0013] Second, there is only one direction of response by dithering any of the waveplates within the polarization controller. On a polarization plot using a Poincare chart, the SOP can be represented as a vector. Poincare charts are used to plot states of polarization in a three-dimensional format. Movement from one SOP to another SOP gives a trace on the Poincare chart. For an example, as shown in FIG. 1(b), a Poincare chart 30 traces the change in SOP from a left circular polarization state at the input of a polarization controller to a linear polarization state at the output, using a QWP-HWP polarization controller. The left circular polarization state is at point A on the sphere. Using the QWP and HWP waveplates alters the input SOP to a linear polarization state along the equatorial plane by means

of a movement 32. Rotating/dithering either the QWP or the HWP can only generate a movement 34 along the circumference of the equatorial plane, and there is no movement along a longitudinal direction. Thus, a conventional polarization controller loses the tracking ability along the longitudinal direction.

[0014] The two situations discussed above are referred to herein as loss control ("LC") effects. Because conventional polarization controller processes make changes to each waveplate for a fixed period of time, they are unable to sufficiently handle loss control problems. Thus, there is a need for new controller methods to address loss control problems.

SUMMARY OF THE INVENTION

[0015] In accordance with aspects of the present invention, a polarization control method is provided. In the method, an input optical signal is received at a first waveplate. The input optical signal has a state of polarization associated therewith. A first rotation direction is selected for the first waveplate. The first waveplate is rotated a first step amount along the first rotation direction to adjust the state of polarization of the input optical signal. A feedback signal is monitored to assess the efficacy of rotating the first waveplate. Rotation of the first waveplate is continued while the feedback signal satisfies a first condition.

[0016] In one example, the first condition is associated with feedback minimization. In another example, the first condition is associated with feedback maximization. In a further example, continuing the rotation of the first waveplate includes incrementing by the first step amount for each rotation of the first waveplate. In one alternative, the first step amount is at least one degree. In another alternative, the first step amount is less than 10 degrees.

In a third alternative, the first step amount is between about two and three degrees.

[0017] In an alternative, the method preferably includes further rotating the first waveplate along the first rotation direction if the feedback signal satisfies a second condition, selecting a reverse rotation direction if the feedback signal does not satisfy the second condition, and rotating the first waveplate a second step amount along the reverse direction if the feedback signal does not satisfy the second condition. This sub-process desirably occurs prior to continuing the rotation while the first condition is satisfied.

[0018] In a further alternative, the method preferably includes ceasing the continued rotation of the first waveplate once the feedback signal does not satisfy the first condition. In this case, a second waveplate may be selected. Then an initial direction of rotation may be selected for the second waveplate. Next, the second waveplate may be rotated along the initial direction of rotation a second step amount to adjust the state of polarization. The feedback signal is monitored to assess the efficacy of rotating the second waveplate. In accordance with this alternative, the second waveplate may continue to be rotated while the feedback signal satisfies a second condition.

[0019] In accordance with aspects of the present invention, a method of controlling a state of polarization is provided. In the method, a plurality of waveplates is provided. A first one of the plurality of waveplates is continually adjusted along a first rotation direction while a feedback signal satisfies a first condition. Adjusting the first waveplate ceases if the feedback signal does not satisfy the first condition. A second one of the plurality of waveplates is continually adjusted along a second rotation direction while the feedback signal satisfies a second condition. Adjusting the second waveplate ceases if the

feedback signal does not satisfy the second condition. A third one of the plurality of waveplates is continually adjusted along a third rotation direction while the feedback signal satisfies a third condition. Adjusting the third waveplate ceases if the feedback signal does not satisfy the third condition.

[0020] In one example, the first, second and third rotation directions are all clockwise. In another example, the first, second and third rotation directions are all counterclockwise. In a further example, the waveplates are arranged in a serial fashion and are adjusted sequentially. Preferably, the first, second and third conditions are equivalent. More preferably, the first, second and third conditions are selected such that the state of polarization is confined within a zone of acceptability. The zone of acceptability may represent about a -20 dB suppression of unwanted orthogonal polarization, and desirably represents a suppression between -5 dB and - 40 dB. Alternatively, the zone of acceptability is selected to minimize loss control effects.

[0021] In accordance with aspects of the present invention, a polarization control system is provided. The system comprises a first optical transmission medium, a plurality of waveplates, a second optical transmission medium, and polarization control logic. The first optical transmission medium is capable of receiving an input optical signal having an input state of polarization. The plurality of waveplates is operatively connected together. A first one of the plurality of waveplates is operable to receive the input optical signal from the first optical transmission medium. The second optical transmission medium is capable of receiving an output optical signal having an output state of polarization from a last one of the plurality of waveplates. The polarization control logic is operable to modify the input state of polarization so that the output state of

polarization is obtained to have a predetermined polarization criterion. The polarization control logic is further operable to select a first direction of rotation for the first waveplates, to rotate the first waveplate a first step amount along the first direction of rotation to adjust the input state of polarization, to monitor a feedback signal to assess the efficacy of rotating the first waveplates, and to continue rotating the first waveplate while the feedback signal satisfies a first condition.

[0022] Various arrangements of waveplates are possible. In an example, there are between five and eight waveplates. In another example, there are between three and twelve waveplates. The waveplates may be arranged in a serial fashion. They may also be adjusted sequentially by the polarization control logic. Preferably, each of the waveplates functions as a quarter wave plate. The waveplates are preferably selected from the group consisting of a $LiNbO_3$ component, a liquid crystal, a fiber loop, and a fiber squeezer. In another example, the predetermined polarization criterion is a zone of acceptability.

[0023] In accordance with aspects of the present invention, a polarization control system is provided. The system comprises a first optical transmission medium, a plurality of waveplates, a second optical transmission medium, and polarization control logic. The first optical transmission medium is capable of receiving an input optical signal having an input state of polarization. The plurality of waveplates is operatively connected together. A first one of the plurality of waveplates is operable to receive the input optical signal from the first optical transmission medium. The second optical transmission medium is capable of receiving an output optical signal having an output state of polarization from a last one of the plurality of waveplates. The polarization control logic is operable to modify the input state of polarization such that the output state of

polarization is obtained to have a predetermined polarization criterion. The polarization control logic is further operable to continually adjust the first waveplate along a first rotation direction while a feedback signal satisfies a first condition, to cease adjusting the first waveplate if the feedback signal does not satisfy the first condition, to continually adjust a second one of the plurality of waveplates along a second rotation direction while the feedback signal satisfies a second condition, to cease adjusting the second waveplate if the feedback signal does not satisfy the second condition, to continually adjust a final waveplate along a last rotation direction while the feedback signal satisfies a third condition, and to cease adjusting the final waveplate if the feedback signal does not satisfy the condition.

[0024] In accordance with aspects of the present invention, a polarization control apparatus is provided. The apparatus comprises a plurality of waveplates, polarization control logic, and a feedback means. The plurality of waveplates are operatively connected together. A first one of the plurality of waveplates is operable to receive an input optical signal having an input state of polarization. The polarization control logic is operable to modify the input state of polarization such that an output state of polarization is obtained at a last one of the plurality of waveplates. The output state of polarization has a predetermined polarization criterion. The feedback means is operable to provide feedback information from the plurality of waveplates to the polarization control logic. The polarization control logic is further operable to select a first direction of rotation for the first waveplate, to rotate the first waveplate a first step amount along the first direction of rotation to adjust the input state of polarization, to monitor the feedback information to assess the efficacy of rotating the first waveplate, and to continue

rotating the first waveplate while the feedback information satisfies a first condition.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] For purposes of illustrating various aspects of the invention and to provide a further understanding of the method and system of the invention, together with the detailed description, the drawings show forms that are presently preferred. It should be understood, however, that the invention is not limited to the precise arrangements and instrumentalities shown.

[0026] FIG. 1(a) illustrates a set of waveplates that are used to change the state of polarization for an input optical signal.

[0027] FIG. 1(b) illustrates an exemplary Poincare chart tracing the change from an input left circular polarization state to an output linear polarization state.

[0028] FIG. 2(a) illustrates a schematic diagram of a polarization multiplexer including a pair of polarization controllers for polarizing signals to be launched into a conventional optical transmission system.

[0029] FIG. 2(b) illustrates a schematic diagram of a polarization demultiplexer including a demultiplexer and a polarization controller for receiving polarized signals from a conventional optical transmission system.

[0030] FIG. 3 illustrates a conventional polarization controller dithering algorithm.

[0031] FIG. 4 illustrates a flow diagram in accordance with aspects of the present invention.

[0032] FIG. 5 illustrates a polarization control process in accordance with the flow diagram of FIG. 4.

[0033] FIG. 6 is a schematic diagram of a polarization controller simulator.

[0034] FIGS. 7(a)(1)-7(c)(2) illustrate three-dimensional state-of-polarization plots using Poincare sphere charts.

[0035] FIGS. 8(a)-(b) illustrate experimental results using Poincare charts in compare conventional polarization control techniques with polarization control methods in accordance with aspects of the present invention.

DETAILED DESCRIPTION

[0036] The present invention addresses loss control ("LC") problems in order to minimize dead spots in the transmission of polarized signals. In accordance with aspects of the present invention, polarization control methods are provided for use with polarization control equipment. As discussed above, conventional polarization control processes manipulate waveplates sequentially for fixed periods of time. It has been discovered that a more flexible approach yields significant and unanticipated benefits over conventional techniques, significantly minimizing LC effects.

[0037] For the first LC effect described above, namely a lack of absolute response by dithering a waveplate, it is desirable to increase the dither step-size of the waveplate when the response (or feedback signal) becomes smaller. In accordance with aspects of the present invention, an adaptive dither algorithm is used because the dither step-size is adjusted according to the response of the waveplate. However, it is difficult to estimate the optimal step-size. In an overcompensation situation, an unnecessarily large dither step-size allows the output SOP deviate too far away from the desired position. On the other hand, insufficient dither step-size operates too slowly to recover the response. The waveplate cannot be moved far enough away from the dead spot by an insufficient dither step-size.

[0038] For the second LC effect, namely that there is only one direction of response by dithering all of the waveplates within a polarization controller, the number of waveplates is preferably increased to reduce the probability that all of the waveplates have a response in the same direction. However, the more waveplates employed, the less time each

waveplate is rotated in a conventional system because they are dithered in sequence for fixed periods of time. Because some of the waveplates may not have a response, the efficacy of a conventional polarization controller may even be reduced by adding more waveplates.

[0039] It has been discovered that it is possible to remove the LC effects by continuing to dither the orientations of selected waveplates while bypassing or cutting short the dithering of other waveplates. For the first LC effect, rather than increase the dither step-size of a waveplate that has no response, it is preferable to remain with a "good" waveplate as long as possible. A "good" waveplate is one that can be employed to change the SOP and/or produce a beneficial response. If there is at least one other waveplate that has a desired response, then it becomes possible to switch to this "good" waveplate, decide a correct rotation direction and keep rotating this waveplate while monitoring the feedback signal.

[0040] Assuming the goal is to try and minimize the feedback signal, the controller preferably rotates the waveplate continuously if the feedback signal decreases monotonically, and switches to the next waveplate if the feedback signal increases. This procedure is explained in more detail with regard to FIG. 4. After returning to a "bad" waveplate in a subsequent cycle, the process can more likely recover the response because other waveplates in the polarization controller have changed by large angles. Note that it possible for a bad waveplate in one cycle to become a good waveplate in the next cycle.

[0041] For the second LC effect, the control speed is not sacrificed by increasing the number of waveplates in the polarization controller. Furthermore, the more waveplates, the larger the probability a good waveplate exists in the polarization controller.

[0042] FIG. 4 is a flow diagram 400 that illustrates a preferred method of achieving a desired response for a given initial SOP in accordance with aspects of the present invention. In the example of flow diagram 400, it is desirable to decrease or minimize the feedback of the system, as will be described below. In an initialization step 402, an index value is set to one (1), identifying the first stage of the dithering and adjusting process for a selected waveplate. Point "A" at step 403 represents a stage in the process after initialization is performed. Then at step 404, a buffer is set equal to a feedback signal. The buffer desirably includes information concerning the SOP associated with the waveplate at a particular step in the polarization control process. The feedback signal is preferably the optical power after the polarization beam splitter. The feedback signal may be monitored throughout the polarization control process. Next, at step 406, the index value is checked. If the index value is one (1), the process proceeds to step 410, in which the rotation direction is set to a positive direction. Preferably, the positive direction is clockwise, although it may be counterclockwise.

[0043] Once the rotation direction is set, the waveplate is preferably dithered by one (1) step in step 412. Depending upon the type of waveplate, it may be dithered mechanically, electrically or by some other technique. The value of a single step in a preferred embodiment of the present invention is on the order of two (2) to three (3) degrees, although the step size may be larger or smaller, for example at least one (1) degree in some cases or less than ten (10) degrees in other cases. As discussed above, overcompensation is undesirable. Thus, in some situations, a step size greater than, e.g., ten (10) degrees may be too large. Similarly, in other situations, under-compensation of, e.g., much less than one (1) degree may not permit the polarization controller to move away from a dead spot rapidly

enough. Therefore, in another preferred embodiment of the present invention, the step size is between one (1) and ten (10) degrees. In yet another preferred embodiment of the present invention, the step size is greater than one-half (0.5) degree and less than five (5) degrees. Once the waveplate is dithered, the index is preferably set to a value of two (2) in step 414, and then returns to the point A at step 403 in the flow diagram 400.

[0044] If the index value checked in step 406 is equal to two (2), the process desirably proceeds to step 420, wherein a pair of feedback signals are compared. Specifically, the current feedback signal of buffer[2] is compared to the previous feedback signal of buffer[1], which preferably includes state information prior to dithering the current waveplate (not shown). If the previous feedback signal of buffer[1] is greater than the current feedback signal of buffer[2], the process proceeds to step 422, otherwise it proceeds to step 424. If buffer[2] is smaller than buffer[1], this indicates that the dithering is reducing the feedback. Thus, in step 422, the waveplate is preferably dithered/rotated by an additional step along the direction set in step 410 to continue reducing the feedback signal. The additional step may be of the same or different size than that selected in step 412. However, if buffer[2] is the same or larger than buffer[1], this indicates that the initial dithering of step 412 is not reducing the feedback signal. In that case, a negative rotation direction is preferably set in step 424.

[0045] If the initial rotation direction of step 410 was clockwise, then the new rotation direction of step 424 is counterclockwise. Then in step 428, the waveplate is preferably dithered by rotating two steps in the new rotation direction. These two (2) steps may be of a different size than that selected in step 412, although they are both preferably the same size. After the rotation is performed in

either step 422 or step 426, the index value is set to three (3) in step 428, and the process then returns to point A in step 403 of the flow diagram 400.

[0046] If the index value checked in step 406 is equal to three (3), the process proceeds to step 430, wherein the current feedback signal of buffer[3] is compared to the previous feedback signal of buffer[2]. If the previous feedback signal of buffer[2] is greater than the current feedback signal of buffer[3], the process proceeds to step 432, otherwise it proceeds to step 436. If buffer[3] is less than or equal to buffer[2], this indicates that the dithering is reducing the feedback. Thus, in step 432, the waveplate is preferably dithered/rotated by an additional step along the rotation direction. This additional step may be of the same or different size than that selected in step 412 or other steps in this process.

[0047] After the rotation is performed in step 432, the buffer[2] value is preferably set equal to the buffer[3] value in step 434, and the process then returns to point A at step 403 in the flow diagram 400. This enables the process to continue reducing the feedback signal. The system continues adjusting the current waveplate so long as the feedback signal is not increasing. However, if buffer[3] is greater than buffer[2], this indicates the dithering/manipulating of the current waveplate is not reducing the feedback signal. In that case, adjustment of the current waveplate desirably ceases and the process advances to a subsequent waveplate in the polarization controller in step 436.

[0048] Preferably, the subsequent waveplate is the next waveplate in the polarization controller. For example, if there are six waveplates in the polarization controller and the current waveplate is number 3, the next waveplate on which dithering will be performed is preferably number 4.

Similarly, if the current waveplate is number 6, the next waveplate is preferably number 1.

[0049] It should be understood that instead of attempting to decrease or minimize the feedback signal, the system could be operated to achieve a different condition, such as increasing or maximizing the feedback signal. In that case, the buffer comparisons at steps 420 and 430 would be reversed. Specifically, if buffer[2] is greater than buffer[1] at step 420, this indicates the dithering is increasing the feedback signal. Thus, in step 422, the waveplate is preferably dithered/rotated by an additional step along the direction set in step 410 to continue reducing the feedback signal. The additional step may be of the same or different size than that selected in step 412. However, if buffer[2] is the same or less than buffer[1], this indicates the initial dithering of step 412 is not increasing the feedback signal. In that case, a negative rotation direction is set in step 424. Similarly, at step 430, if the previous feedback signal of buffer[2] is less than the current feedback signal of buffer[3], the process proceeds to step 436, otherwise it proceeds to step 432.

[0050] FIG. 5 illustrates polarization control in accordance with system operation as described in relation to the flow diagram of FIG. 4. As shown in FIG. 5, if adjustments $\Delta\alpha$ and $\Delta\beta$ to waveplates 1 and 2, respectively, do not cause a reduction in the feedback signal, the system advances to adjusting waveplate 3. The process preferably continues adjusting waveplate 3 so long as there is a reduction in the feedback signal (assuming feedback minimization is desired). Once the feedback signal increases, adjustment $\Delta\gamma$ to waveplate 3 preferably ceases and the system advances to the next waveplate, which in this illustration is waveplate 1. As discussed previously, if this had been a system having 4, 5, 6 or more waveplates, the

adjustment would have advanced to the next waveplate, e.g. waveplate 4.

[0051] In order to compare the performance between the conventional dither algorithm and an algorithm in accordance with aspects of the present invention, a simulation was performed employing the structure shown in FIG. 6. A polarization controller 602 receives an input signal from a transmitter 600 through first polarization scrambler 604, and sends an output signal to a second polarization scrambler 606. The first and second polarization scramblers 604, 606 simulate single-mode long haul transmission fibers. It should be understood that multi-mode transmission fibers may also be used in accordance with the present invention. The output signal is then passed through a coupler 608 to a monitor 610 and to a polarization splitter 612. The monitor 610 evaluates the SOP, and the polarization splitter 612 provides a feedback signal to the polarization controller 602.

[0052] Three types of polarization controllers 602 were employed in the simulations. They were (1) QWP-HWP-QWP, (2) QWP-QWP-QWP-QWP-QWP, and (3) QWP-QWP-QWP-QWP-QWP-QWP. The waveplate angle was dithered by three (3) degrees (i.e., step size) every 100 us. The front scrambler adjusted the SOP by 3500 degrees/s, and the back scrambler adjusted the SOP by 350 degrees/s.

[0053] FIGS. 7(a)(1)-7(c)(2) compare the performances of the conventional dither process described above with reference to FIGS. 1-3 and a new control algorithm in accordance with aspects of the present invention for the three types of polarization controllers 602 using Poincare charts. FIGS. 7(a)(1), 7(b)(1) and 7(c)(1) are Poincare charts for the conventional process for the QWP-HWP-QWP, QWP-QWP-QWP-QWP-QWP and QWP-QWP-QWP-QWP-QWP-QWP polarization controllers, respectively. FIGS. 7(a)(2), 7(b)(2) and 7(c)(2) are Poincare charts for the processes of the instant

application for the QWP-HWP-QWP, QWP-QWP-QWP-QWP-QWP and QWP-QWP-QWP-QWP-QWP-QWP polarization controllers, respectively. When viewing the conventional dithering process, it can be seen that the most effective performance occurred with the QWP-HWP-QWP polarization controller. There was no benefit by increasing the number of waveplates. On the other hand, when viewing FIGS. 7(a)(2), 7(b)(2) and 7(c)(2), it can be seen that the number of the LC effects is reduced significantly. For each given waveplate configuration, the Poincare charts illustrate that the present invention generated highly focused polarization results. Significant polarization control was achieved, in contrast to the conventional processing. Importantly, increasing the number of waveplates reduced the probability of the LC effects.

[0054] In addition to the simulations, experimental results were also obtained using the configuration of FIG. 6. An Agere Systems Inc. $LiNbO_3$ model 2722 system having 5 QWPs was used as the polarization controller 602. The second and the third QWPs were synchronized together to act as a HWP. The fifth QWP was not used. Therefore, the experimental polarization controller 602 had a QWP-HWP-QWP structure. One Agilent Technologies (HP) 11896A polarization scrambler was inserted before the polarization controller, acting as the polarization scrambler 604. The scrambling speed was set to a rotational rate of 360 degrees/s. After the polarization controller 602, an Agilent Technologies (HP) 8509B polarization analyzer was employed as the monitor 610 to monitor the output SOP.

[0055] The experimental results are plotted on the Poincare charts in FIGS. 8(a) and 8(b). In the figures, circle 802 represents a "zone of acceptability" for the SOP. The desired polarization should be a single point on the Poincare sphere. However, due to the unwanted orthogonal polarization, this may not be the case. Thus, the zone of acceptability places a limit on the deviation due to the

unwanted orthogonal polarization. As seen in the figures, the circle 802 on the surface of the Poincare sphere has a normalized radius of 0.198, which equates to a -20 dB suppression of the unwanted orthogonal polarization state. The amount of suppression may vary depending upon factors such as the number of waveplates employed. The -20 dB suppression value is a preferred value. In a preferred embodiment, the amount of suppression varies between -10 dB and -30 dB. In yet another embodiment, the amount of suppression may vary between -5 dB and -40 dB. The suppression may be higher or lower depending upon the characteristics of the system, cost constraints and other implementation details.

[0056] FIG. 8(a) illustrates the results of the conventional process described above with reference to FIGS. 1-3, and FIG. 8(b) illustrates the results of a process in accordance with aspects of the present invention. As seen in FIG. 8(a), the conventional process significantly oversteps the zone of acceptability. In contrast, when employing a process in accordance with aspects of the present invention, the output SOP illustrated in FIG. 8(b) is much more tightly controlled and barely reaches the outer boundary of the zone of acceptability at a few points. This indicates that the LC effects are substantially avoided.

[0057] Multiple or varied zones of acceptability may be utilized to achieve desired statistical results. For instance, in a preferred embodiment, the zone of acceptability may be set such that approximately 67% (or one standard deviation) of the SOP signal has a suppression of -40 dB. In another preferred embodiment, the zone of acceptability may be set such that approximately 95% (or two standard deviations) of the SOP signal has a suppression of -15 dB. In yet another preferred embodiment, the zone of acceptability may be set such that approximately one standard deviation of the SOP signal is suppressed on the order of -30

dB. and approximately two standard deviations of the SOP signal are suppressed on the order of -10 dB. In a further preferred embodiment, a first zone of acceptability may be set such that approximately one standard deviation of the SOP signal is suppressed by between -20 dB and -40 dB, and a second zone of acceptability may be set such that approximately two standard deviations of the SOP signal are suppressed by between -5dB and -20 dB.

[0058] While the experimental system only tested the QWP-HWP-QWP configuration, it is apparent from the simulations that increasing the number of waveplates result in significant improvements to the output SOP. The primary limitation on the number of waveplates is cost. Thus, in preferred embodiments, the polarization controller may comprise between five (5) and eight (8) QWPs. In a situation where cost is not a factor, the polarization controller preferably includes between six (6) and twelve (12) QWPs. In a situation where cost is a significant factor, the polarization controller preferably includes between three (3) and six (6) QWPs. Desirably, the QWPs are not integrated or otherwise combined to form HWPs. Alternatively, it is possible to place two or more polarization controllers in tandem. This will enable off-the-shelf controller equipment to be employed.

[0059] Although the invention herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present invention. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present invention as defined by the appended claims.